INVESTIGATION OF HIGH-SPEED IMPACT PHENOMENA (IV)

FINAL REPORT

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1. INTRODUCTION

This report summarizes the results obtained from a research program conducted for the NASA by TRW Systems under the terms of NASA Contract NASw-1336. The principal objective of the program was to study experimentally the interaction of high velocity particles with gaseous targets using the TRW Systems electrostatic particle accelerator. Emphasis was placed on the laboratory simulation of meteor phenomena and the first direct experimental measurements of meteor ionization and luminous efficiencies were completed under the auspices of this program. The initial measurement of ionizing efficiency which used iron particles and air targets was expanded to encompass a variety of target gases. Finally, drag coefficients were precisely measured under free-molecule flow conditions for relatively low velocity particles. As a result of this experiment, a modified free-molecule drag model was developed.

All of these experiments have been described in a series of four Technical Reports which were submitted upon completion of each experiment. In essence, these reports comprise the Final Technical Report of this program and abstracts of each report are attached as appendices. The brief discussion given in the following sections provides background information relating to this series of experiments.

2. METEOR SIMULATION EXPERIMENTS

Much of what is known about meteoroids in space has been deduced from photographic observations of luminous trails and radar probing of ionized wakes produced by meteoroids entering the earth's atmosphere. A meteoroid of mass m and velocity v entering an atmosphere of density ρ is decelerated at the rate

$$\frac{dv}{dt} = -\frac{\Gamma A \rho v^2}{m} \qquad (1)$$

where Γ is the drag coefficient and A is the projected area of the meteor. The rate of mass loss dm/dt is given by

$$\zeta \frac{dm}{dt} = - \frac{\Lambda}{2} A\rho v^2 \tag{2}$$

where ζ is the heat of ablation and Λ is the heat transfer coefficient. The primary ablation mechanism is assumed to be vaporization; hence ζ is the energy per unit mass required to vaporize the meteor. The heat transfer coefficient gives the fraction of meteor kinetic energy converted to internal energy of the meteor.

The observable quantities for meteors in the earth's atmosphere are the luminous trail and the ionized wake. From contemporary meteor theory, the instantaneous luminous intensity of the trail I_p and the energy expended per unit time in creating ion-electron pairs I_q are both proportional to the rate of mass loss. Hence, one can write,

$$I_p = - \frac{1}{2} \tau_p v^2 \frac{dm}{dt} \tag{3}$$

and

$$I_q = - \frac{1}{2} \tau_q v^2 \frac{dm}{dt} \quad . \tag{4}$$

The symbols τ_p and τ_q, which are designated as the meteor luminous efficiency and meteor ionizing efficiency, respectively, are defined by these equations and it can be seen that they represent the fraction of meteor kinetic energy expended in producing radiation and ionization. It is generally more convenient to express the ionization process in terms of the ionizing probability β:

$$\frac{dn}{dt} = -\frac{\beta}{\mu}\frac{dm}{dt} \quad . \tag{5}$$

Here dn/dt is the number of ion pairs created per unit time and μ is the mass of the evaporated atom. β is the ratio of the number of ions formed to the number of atoms available to create ion pairs and is related to τ_q by

$$\tau_q = \frac{2\phi}{\mu v^2}\beta \tag{6}$$

where ϕ is the ionization potential of the atom.

For high initial velocities, it can be shown that the meteoroid is essentially totally vaporized while suffering negligible deceleration. For this special case, $\int dm/dt$ becomes m_o, the initial mass of the meteoroid. Thus, in integral form Eqs. (3) and (5) become

$$E_p = \tau_p \frac{1}{2} m_o v_o^2 = \tau_p E_o \tag{7}$$

and

$$N_I = \frac{\beta}{\mu} m_o = \beta N_A \tag{8}$$

where E_p is the total radiant energy from the luminous trail, E_o is the initial kinetic energy of the meteoroid, N_I is the total number of ion-electron pairs in the meteor wake, and N_A is the number of atoms contained in the meteoroid.

The quantities τ_p and β are of crucial importance in interpreting the observations of natural meteors. Prior to the work conducted under this program, there had not been a satisfactory laboratory measurement of either quantity. Presently accepted values of τ_p and β are based on basic analytical treatments of the problem and phenomenological observations of natural meteors. The possible errors are admittedly large.

In this program, the experiments were implemented by injecting particles of known velocity and mass into low pressure gas targets and measuring the resultant radiation or ion production. Initial particle velocities ranged from about 20 to 45 km/sec which is in the range where total mass ablation occurs. The main differences between these experiments and natural meteor phenomena are the size of the particle and the absolute pressure of the target gas. Since excitation and ionization arise from reactions on an atomic scale, the difference in particle size appears to be no consequence. The effect of higher gas pressure, which decreases the collisional mean free path of vaporized atoms, is more difficult to assess, but it probably does not alter the experimental results significantly.

An abstract of the Technical Report entitled "Ionization Probability of Iron Particles at Meteoric Velocities" is given in Appendix A. This report gives the results of measurements of ionization probabilities for iron particles incident on target gases of air and argon. The value obtained for air is somewhat greater than the presently accepted value.

An abstract of the report describing the experiment to determine meteor luminous efficiency is contained in Appendix B, "Laboratory Measurement of Meteor Luminous Efficiency". In this experiment, luminous efficiencies were determined for iron particles incident on target gases of air, nitrogen, oxygen, and argon. For air, the luminous efficiency as defined by Eq. (7) was found to be nearly constant with velocity between 20 and 40 km/sec. The average measured value was 0.005 for the spectral range $3400 < \lambda < 6300$ A. The nearly constant value of τ_p over the entire velocity range is in contradiction to generally accepted meteor theory. However, the results are in general agreement with Öpik's theory for meteors with greatly diluted comas.

Most natural meteors are of cometary origin and they are composed of a number of different elements. Unfortunately, all of the important elements are not available in a form compatible with the electrostatic acceleration technique (or other techniques either). Due to the fact that little experimental information is available from any source for the velocity range covered by meteors, it seems appropriate to compile as much data as possible using all of the combinations of particle material and target gases available. As the first step in this process, ionization probabilities were measured for iron particles and target gases of helium, neon, nitrogen, oxygen, carbon dioxide and air. An abstract of the Technical Report describing these measurements is given in Appendix C, "Ionization from Fe Atoms Incident on Various Gas Targets". Ionization cross-sections can be estimated from the ionization probability data and, for the particular case of Fe $\rightarrow N_2$, data obtained from this experiment are in qualitative agreement with published data obtained using more conventional techniques. Another significant factor noted is that the rate of change of β with velocity is systematically greater for monatomic target gases than for diatomic or triatomic target gases.

3. LOW VELOCITY DRAG EXPERIMENT

Although extensive studies of aerodynamic flow problems have been conducted by a variety of techniques, it is still not possible to accurately predict the drag force acting on spheres in free-molecule flow. For many applications sufficiently accurate estimates may be made, but for some applications, e.g., satellite drag, more precise information is required. Accordingly, an experiment to determine drag coefficients for low velocity (near Mach 1) spheres was undertaken. At low velocities, the drag coefficient is a relatively strong function of velocity and results from experiments in this velocity regime provide a severe test of the analytical models used to describe sphere drag.

The "free flight" ballistic range technique was used to determine drag coefficients for iron spheres in a rarefied air target. The velocity and mass of particles from the electrostatic accelerator were determined by the usual techniques and the average velocity of the decelerating particles was determined by means of a velocity measurement range in the gas target chamber.

Drag coefficients were obtained for spherical iron particles for initial velocities ranging from about 0.5 to 3.5 km/sec.

It was found that, of contemporary models, the Schamberg model gave the best fit to the experimental data. However, significant deviations were noted at low velocities. The discrepancy was attributed to a systematic variation in the thermal accommodation coefficient with particle velocity. Following modification of the Schamberg model, it was concluded that the atom-surface collisions range from specular at large velocities to nearly completely diffuse at low velocities. These results are not unambiguous, but they do give a plausible representation of the experimentally derived data. An abstract of the Technical Report describing this experiment is given in Appendix D, "Drag Coefficients of Microscopic Spheres in Free-Molecule Flow".

APPENDIX A

IONIZATION PROBABILITY OF IRON PARTICLES AT METEORIC VELOCITIES*

by J. C. Slattery and J. F. Friichtenicht

ABSTRACT

The number of ion pairs produced by the total ablation of iron particles in air and argon was measured as a function of particle velocity. Micron size iron particles of known mass and velocity were injected into a gas target chamber and the resultant ionization collected with a parallel plate ionization chamber. Initial velocities of the particles ranged from 20 km/sec to 45 km/sec. The ionization probability β, for an iron particle in argon was found to be $\beta = 2.74 \times 10^{-20} v^{4.13}$, where v is the particle velocity in meters/sec. The ionization probability of an iron particle in air was found to be $\beta = 2.60 \times 10^{-15} v^{3.12}$, with v in meters/sec.

*To be published in January 1967 Astrophysical Journal.

APPENDIX B

A LABORATORY MEASUREMENT OF METEOR LUMINOUS EFFICIENCY

by J. F. Friichtenicht, J. C. Slattery, and E. Tagliaferri

ABSTRACT

The luminous efficiency τ_x, as defined in meteor theory, has been determined by measuring the total radiant energy from luminous trails produced by injecting high velocity, sub-micron diameter, iron particles into gaseous targets. The high velocity particles were obtained from an electrostatic particle accelerator and the velocity and mass of each particle was measured prior to entering the gas. Particle velocities ranged from about 15 km/sec to 40 km/sec. In this velocity range, the particles are completely vaporized while suffering small deceleration, which is also the case for most natural meteors. The total radiant energy from the trail was determined by means of a calibrated photomultiplier tube.

The luminous efficiency in the spectral band 3400-6300 A for an air target and iron particles was found to be nearly constant over the velocity interval from 20 to 40 km/sec. This is in agreement with the theoretical treatment of Öpik for meteors with greatly diluted comas. However, the average value of τ_x was about 0.005 which is about two or three times larger than Öpik's predicted value. At 20 km/sec the results are in good agreement with the value given recently by Verniani. However, Verniani's results indicate a linear velocity dependence. Hence the agreement deteriorates at higher velocities.

APPENDIX C

IONIZATION FROM Fe ATOMS INCIDENT ON VARIOUS GAS TARGETS

by J. F. Friichtenicht, J. C. Slattery and D. O. Hansen

ABSTRACT

Ionization probabilities, β, have been measured for iron atoms incident upon target gases of He, Ne, N_2, CO_2, and air. The energetic Fe atoms are obtained by injecting solid iron particles of known velocity and mass into a low pressure gas target where collisional heating raises the temperature of the particle to the vaporization point. Atoms evaporated from the particle traverse the gas at a velocity essentially equal to the velocity of the solid particle and these atoms constitute the atomic "beam". For velocities in excess of $\sim$ 20 km/sec the incident particle is completely vaporized and the number of atoms injected into the target gas, N_A, is specified by the particle mass. The number of ions produced in the target volume, N_I, is determined by means of a parallel plate ionization chamber. By definition, $\beta = N_I/N_A$. An estimated value of the ionization cross-section σ_I can be obtained from these results and for the particular case of Fe atoms incident on a N_2 target, the data are in qualitative agreement with published data obtained using more conventional techniques.

APPENDIX D

DRAG COEFFICIENTS OF MICROSCOPIC SPHERES IN FREE-MOLECULE FLOW

by A. S. Hersh, J. F. Friichtenicht and J. C. Slattery

ABSTRACT

The "free flight" technique has been utilized to determine average drag coefficients C_D for microscopic spherical iron particles in free-molecule flow ($K_n >> 1$). Particles ranging in velocity from about 0.5 to 3.5 km/sec were obtained from an electrostatic particle accelerator. For an air background gas, the flight speed ratio extends from the nonhyperthermal regime ($S_{min} \simeq 1$) well into the hyperthermal region ($S_{max} \simeq 9$). In this regime, C_D for spheres is relatively sensitive to the details of atom-surface interactions and precise measurements of C_D provide a basis for inferring characteristics of these interactions. The experimental results were compared to the free-molecule models of Schamberg and Schaaf-Chambre. The Schamberg model gives a better representation of the experimental data, but significant deviations are noted at low speed ratios. The discrepancy has been attributed to variations in accommodation coefficient, α, and type of re-emission (i.e., specular or diffuse) with speed ratio. Following modification of Schamberg's model, the type of re-emission required to force a fit to the experimental data was evaluated by assuming Epstein's model for the variation of α with S. It was concluded that the atom-surface collisions range from specular at large S to nearly completely diffuse for small S. Although the results are not unambiguous, they do give a plausible representation of the experimentally derived data.